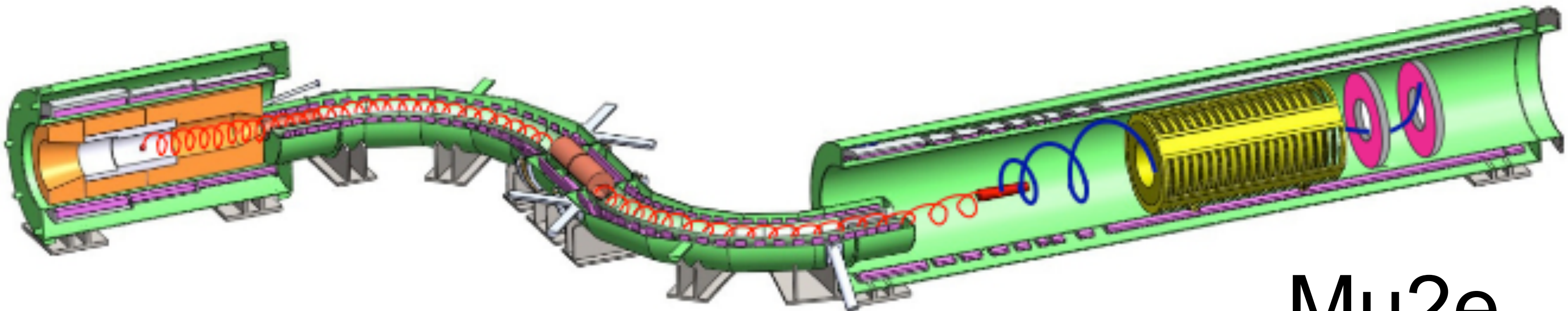

Mu2e

P5 Report
Dec. 16, 2013

Ron Ray
Mu2e Project Manager

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

US-Japan

INFN

Charge

1) a brief summary of the physics case coupled with the explicit scope of the experiment, and a notional timeline for construction start, data taking, and specific anticipated results. What makes this experiment unique, and how does fit in the overall picture of this area?
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Mu2e

- Mu2e is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \longrightarrow e^- N$
- Target sensitivity has great discovery potential
  - Goal: Single-event-sensitivity of 2×10^{-17} (relative to ordinary μ capture)
  - Goal: <0.5 events background
    - Yields Discovery Sensitivity for all rates > few 10^{-16}
- Most new physics models so far postulated provide new sources of flavor phenomena
- Quark flavor is violated. Neutrino flavor is violated.
  - Both implied something profound about the underlying physics
  - Both garnered Nobel Prizes
- What about charged lepton flavor?

Charged Lepton Flavor Violation

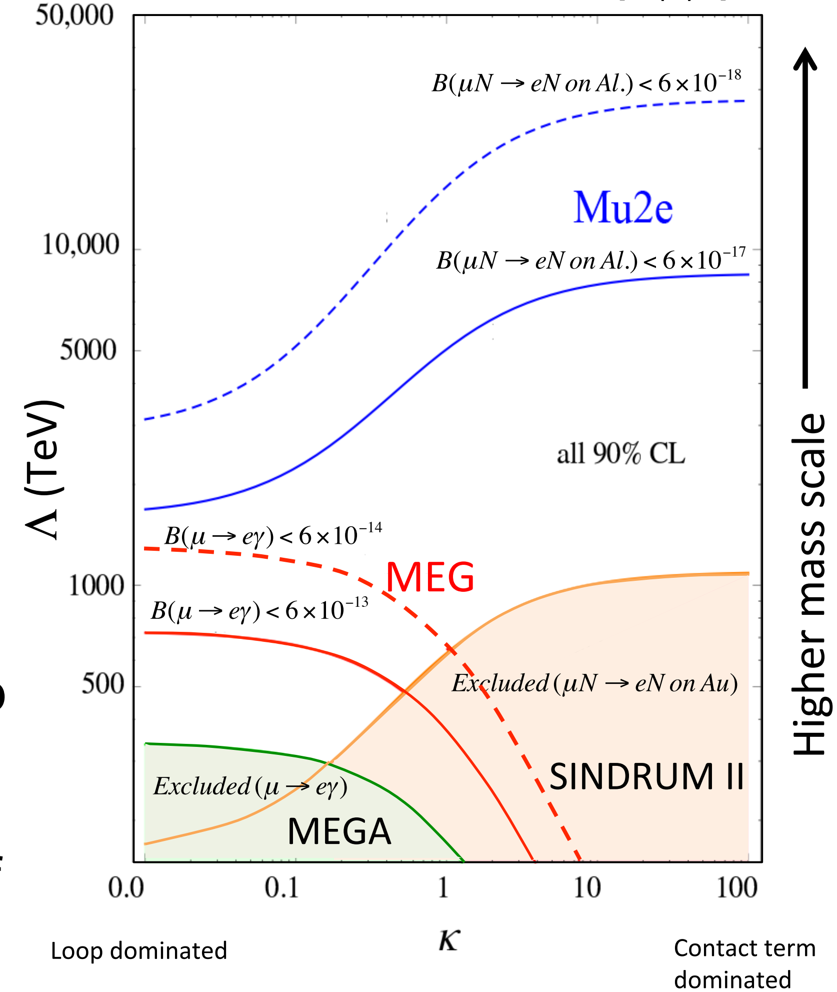
- Significant worldwide interest from Energy and Intensity Frontiers and the theoretical community
  - Rare CLFV decays of μ, τ, K, B-mesons
- Rates negligible in νSM but a wide array of new physics models predict rates that are measurable in next generation experiments.
- Rates of CLFV processes are model dependent and vary widely depending on the underlying physics.
  - CLFV processes are powerful discriminators.
- The most stringent limits on CLFV come from muons because of the relative "ease" of producing an intense source.
- Muon-to-electron conversion offers excellent discovery potential across a breadth of models and will explore impressive mass scales.

What Makes Mu2e Unique?

A. de Gouvêa, P. Vogel
arXiv:1303.4097 [hep-ph]

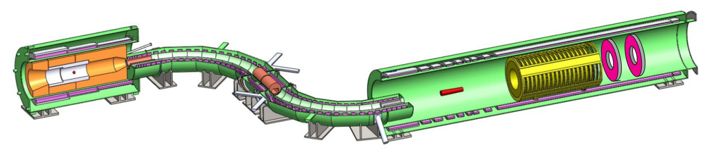
Muon-to-electron conversion is a unique probe of physics beyond the standard model

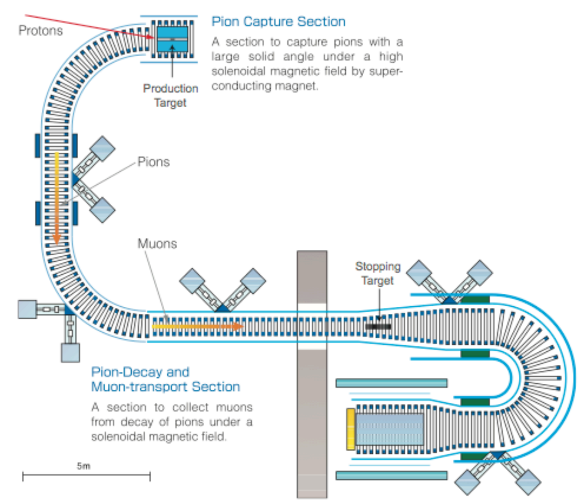
- Broad discovery sensitivity across all categories of models
  - Sensitive to the same physics as MEG but with better mass reach.
  - Sensitive to physics that MEG is not
- Sensitivity to Λ up to 10,000 TeV, well beyond any imaginable accelerator
- Sensitive to new physics at LHC that is suppressed by small mixing angles, loop factors
- Sensitive to new physics at 10 TeV, beyond reach of LHC but within reach of 100 TeV pp collider



What Makes Mu2e Unique?

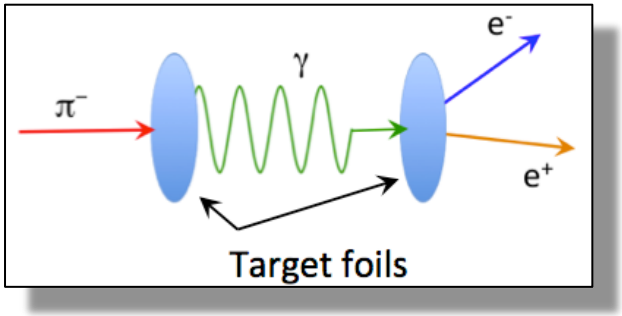
- Mu2e and COMET Phase II have similar capabilities.
- COMET designed to operate at 56 kW, Mu2e at 8 kW.
  - COMET takes all of JPARC beam, so need to acquire data quickly.
  - Mu2e runs simultaneously with neutrino program
- Final bend after COMET's stopping target efficiently transmits conversion electrons and provides needed suppression of rates in detectors but does not transmit positrons.
  - COMET solenoids ~10 m longer than Mu2e
- Higher beam power carries a significant cost
  - Shielding of solenoids (Tungsten)
  - Neutron shielding
- Longer solenoids carry a significant cost





What Makes Mu2e Unique?

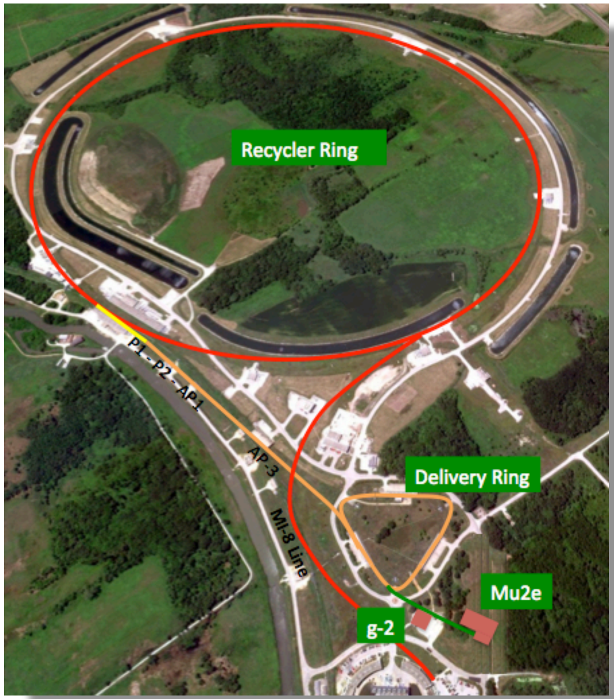
- Mu2e can simultaneously see electrons and positrons from the stopping target
  - Access to additional physics mode: $\mu^- N(Z,A) \rightarrow e^+ N(Z\text{-}2,A)$
    - (ΔL=2 transition – charged analog of neutrinoless double beta decay)
  - High energy positrons are an additional handle on radiative backgrounds with converted photons

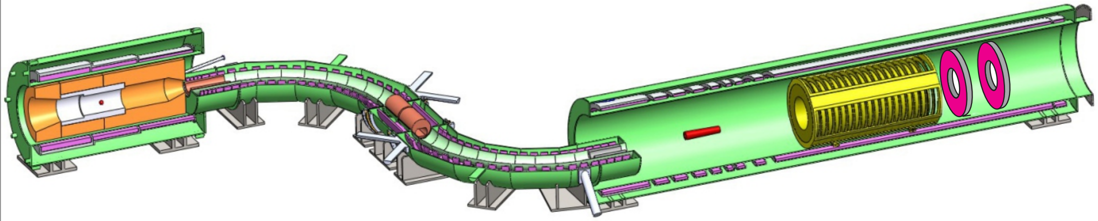


- Mu2e is the fastest, cheapest path to broad discovery sensitivity in CLFV sector.

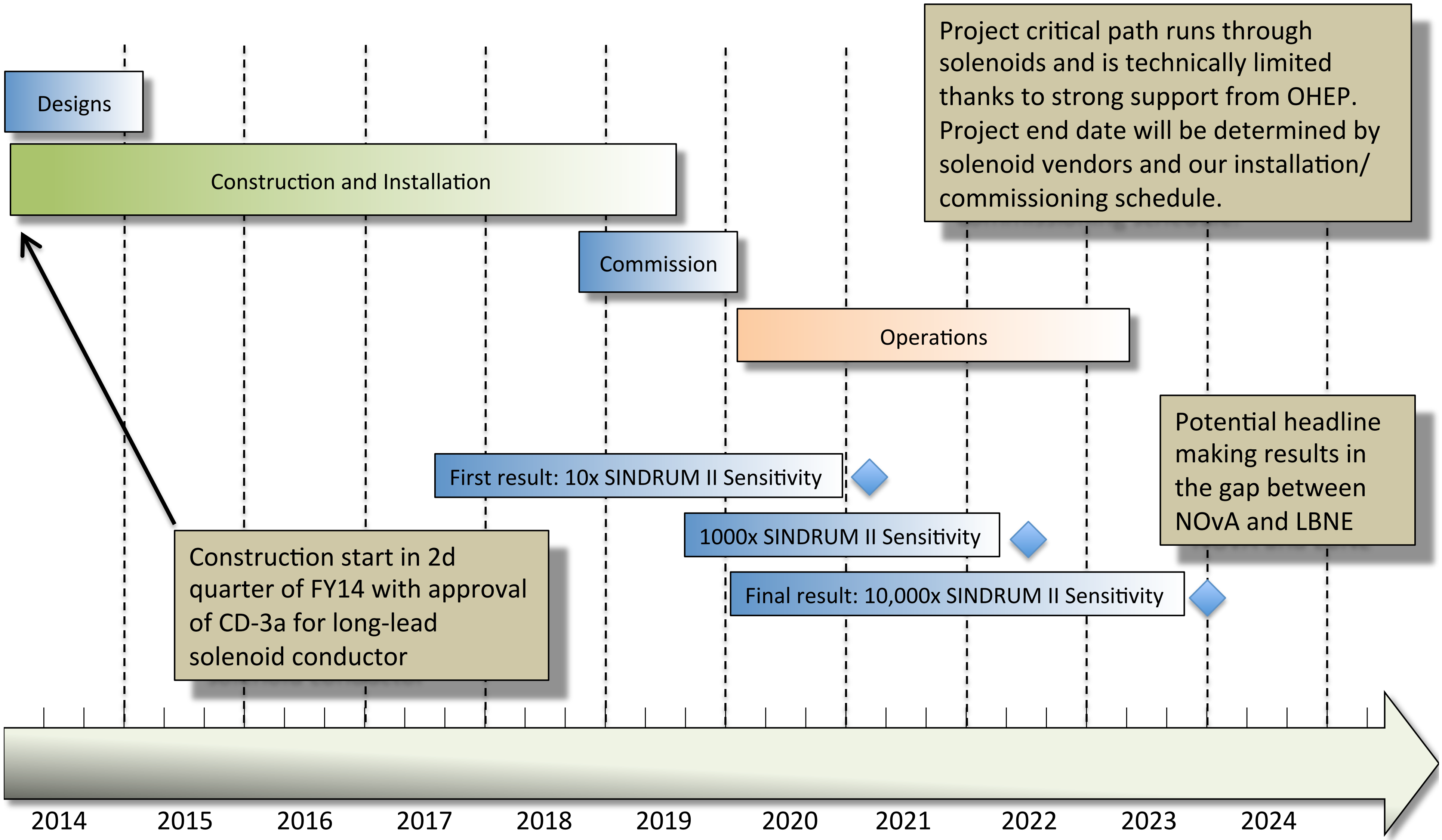
Project Scope

- Upgrades to the existing accelerator complex and construction of a new beamline
- Mu2e Apparatus
  - Superconducting solenoids
  - Tracker
  - Calorimeter
  - Cosmic Ray Veto
  - Stopping target Monitor
- New detector hall





Schedule (CY)


Designs
Construction and Installation
Commission
Operations
Project critical path runs through solenoids and is technically limited thanks to strong support from OHEP. Project end date will be determined by solenoid vendors and our installation/ commissioning schedule.
First result: 10x SINDRUM II Sensitivity
1000x SINDRUM II Sensitivity
Final result: 10,000x SINDRUM II Sensitivity
Potential headline making results in the gap between NOvA and LBNE
Construction start in 2d quarter of FY14 with approval of CD-3a for long-lead solenoid conductor
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

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Mu2e Collaboration

28 Institutions, ~ 155 Collaborators. Still growing. Currently in discussions with several university groups

Boston University
Brookhaven National Laboratory
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of California, Irvine
University of Illinois
Lawrence Berkeley National Laboratory and University of California, Berkeley
Lewis University
University of Massachusetts, Amherst
Muons Inc.
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Purdue University
Rice University
University of Virginia
University of Washington

Laboratori Nazionali di Frascati
Instituto Nazionale di Fisica Nucleare, Genova
Instituto Nazionale di Fisica Nucleare, Lecce and Universita Marconi Roma
Instituto Nazionale di Fisica Nucleare, Lecce and Universita del Salento
Instituto Nazionale di Fisica Nucleare, Pisa
Universita di Udine and INFN Trieste/Udine

Institute for Nuclear Research, Moscow
Joint Institute for Nuclear Research, Dubna

International Participation

- INFN providing significant portion of the calorimeter
  - No calorimeter without them.
- INFN has also contributed to solenoid R&D
  - ~$750,000 (M&S) invested in R&D on prototype solenoid coils.
  - Significant contribution from experienced magnet group.
- INFN has made critical contributions to simulation effort.
- Dubna is contributing labor to the Cosmic Ray Veto effort
  - Setup of cosmic ray test stand and contribution to test beam effort
  - Significant role in installation and commissioning
  - Considering larger responsibilities

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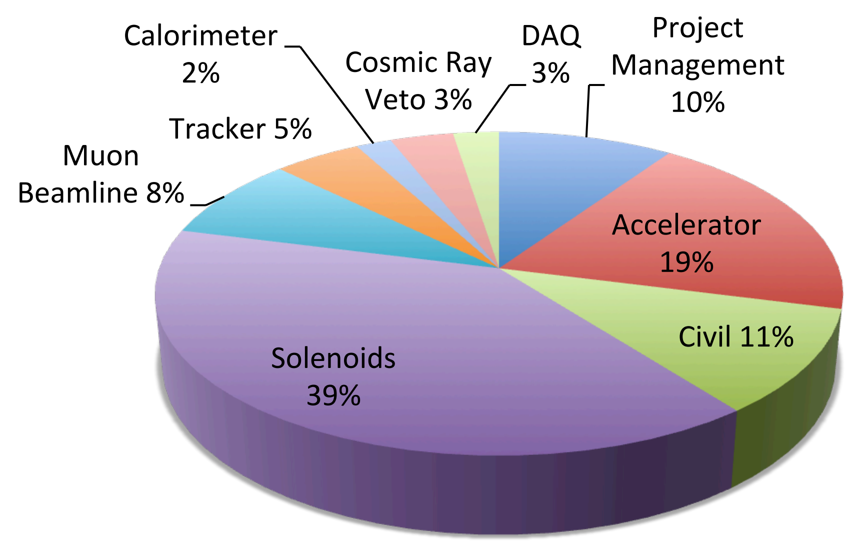
Preliminary Cost Estimate

	Low	High
Actuals through FY13	$36,500	$36,500
Base Estimate to completion	$156,000	$165,000
Contingency on estimate to completion	$54,800	$57,500
Total	**$247,300**	**$259,000**

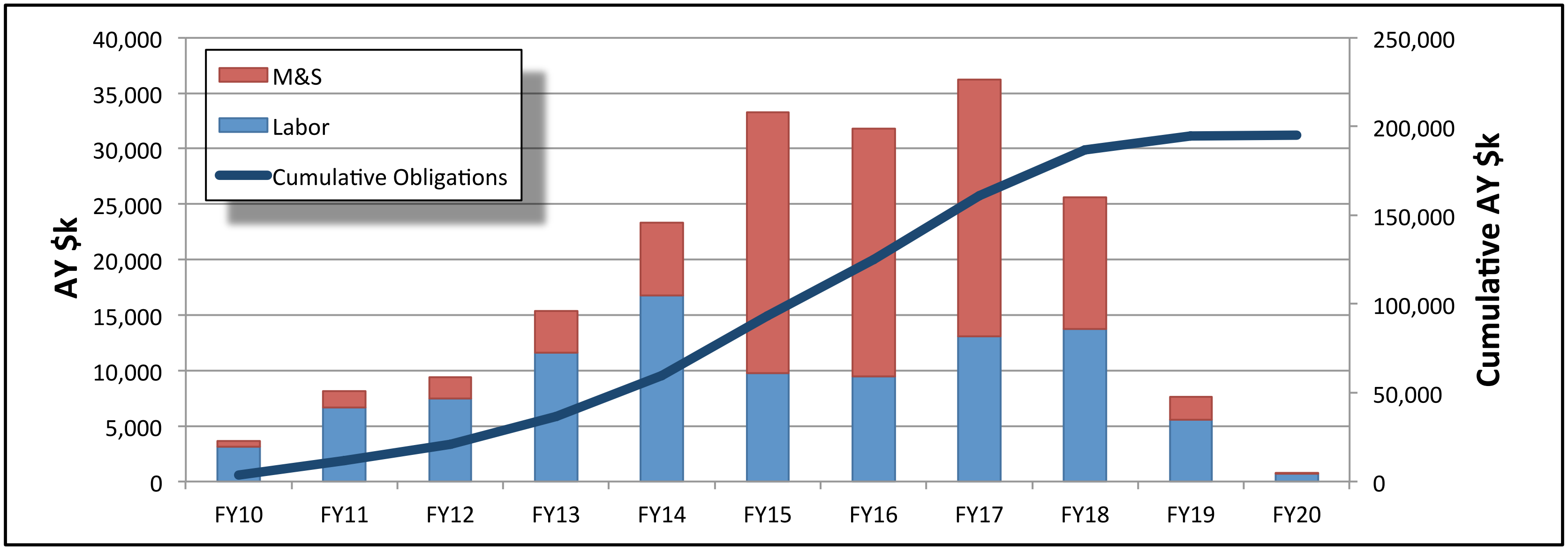
All costs are fully burdened, escalated to actual year.

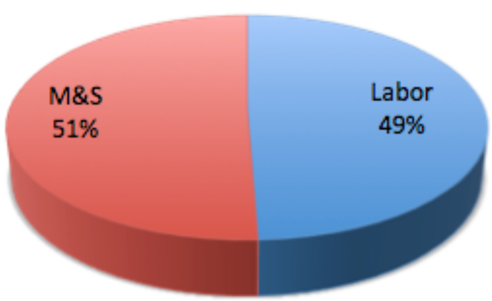
- Remaining uncertainty associated with costing of neutron shielding and detailed planning of installation and commissioning activities.
  - Will be completed soon
- Overall contingency of ~37% on remaining work

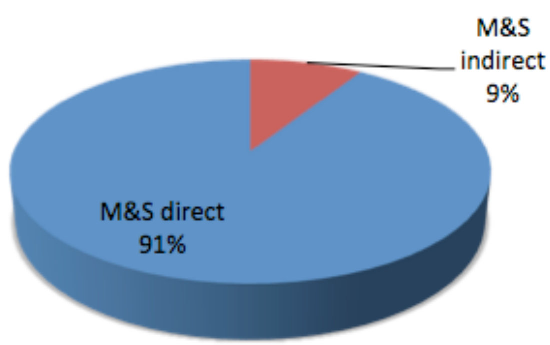


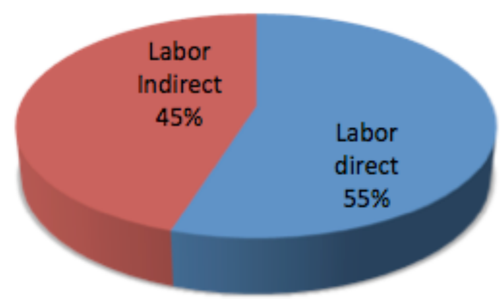
Preliminary Cost Estimate

Obligation Profile – Base cost - Actual year $k









Basis of Estimate

- Project Management
  - Based on NOvA actuals
- Accelerator
  - Engineering designs and lessons learned from NOvA
- Conventional Construction
  - 100% design from A&E and actuals from g-2 building.
  - Vendor quote in hand in time for CD-2
- Solenoids
  - 3 independent estimates of solenoids that agree to 20%
    - RFI with industry (~6 responses)
    - Parametric estimate
    - Bottoms-up estimate
  - Vendor quotes in hand for PS and DS in time for CD-2

Basis of Estimate

- Muon Beamline
  - Engineering designs
- Tracker
  - Engineering designs, prototypes. Experience from CDF tracker, ATLAS straws, BaBar tracker electronics
- Calorimeter
  - Engineering designs, prototypes. Experience from KLOE, BABar.
  - Quotes from crystal vendors
- Cosmic Ray Veto
  - Engineering designs, prototypes
  - Input from NOvA, Minerva actuals for fibers, scintillator, electronics
- DAQ
  - Engineering designs, prototypes
  - NOvA actuals

Project Cost History

Milestone	Total Project Cost (AY$)	Date
CD-0	$200M	November 2009
CD-1	$200M - $300M	July 2012
Current	$247M - $259M	

All costs are fully burdened, escalated to actual year and include contingency.

- No engineering input for CD-0. Used costs from other projects
- Cost range at CD-1 was established using risks and opportunities applied to a bottoms up resource loaded cost and schedule.
  - Significant scope reduction and value engineering prior to CD-1 to stay within acceptable envelope.
    - De-scoped beam power from 25 kW to 8 kW.
    - Saved ~$80M and significantly reduced technical risk associated with beam delivery and shielding
- Current cost is in the middle of the CD-1 cost range.

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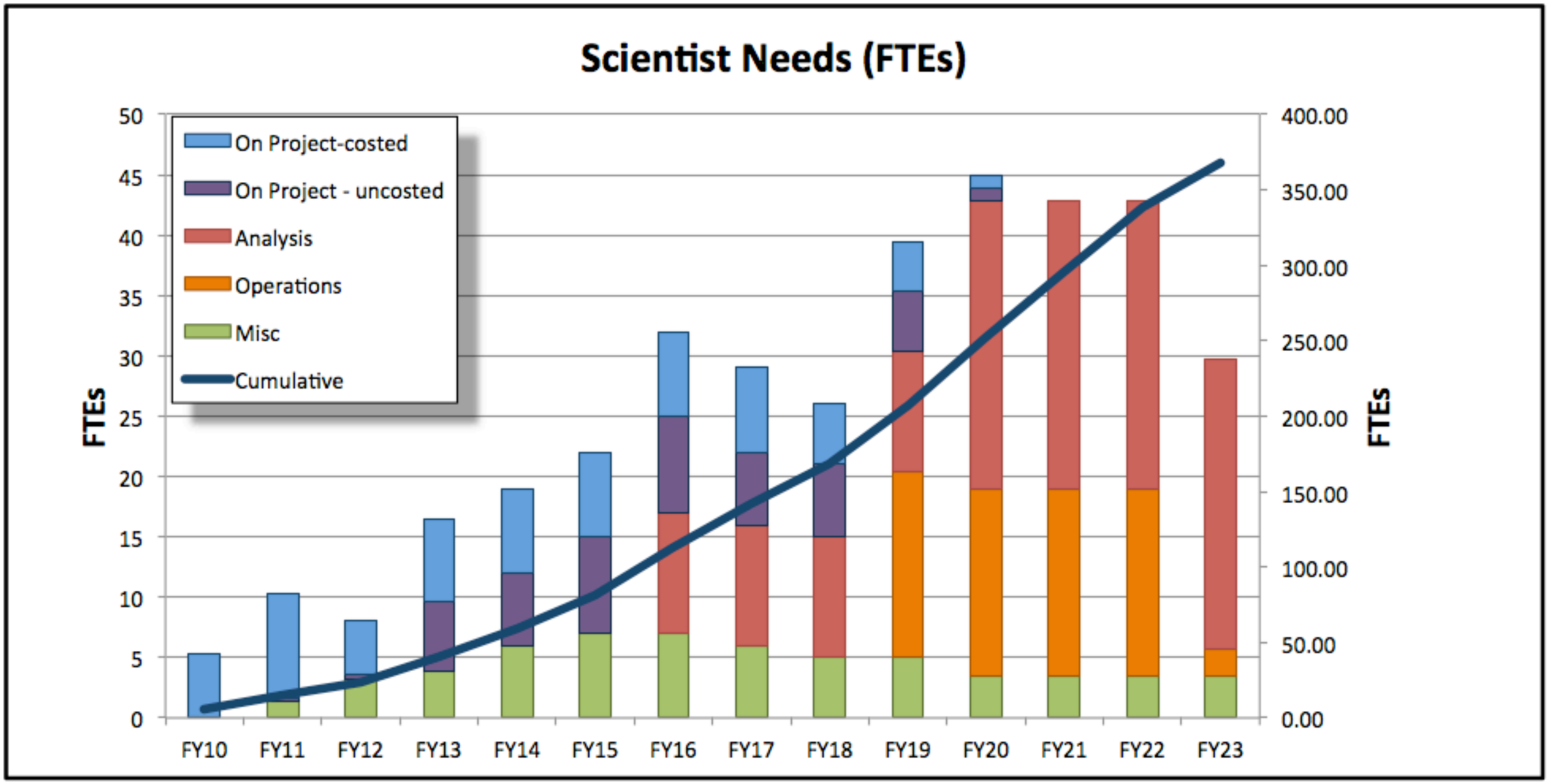
Scientific FTEs

1 FTE =1768 hours



Included in Scientific FTEs

- Online Operations
  - People who carry pagers
  - Detector calibration
  - Data quality monitoring
  - Shifts
- Offline Operations
  - Calibration coordinator
  - Production farms
  - Simulations
  - Ntuples
  - Framework
- Analysis Preparation
  - Alignment
  - Momentum and energy calibration
  - Trigger studies
  - Analysis Coordination
- Analysis Groups
  - Individual backgrounds
  - Physics groups
- Misc
  - Spokespersons
  - Editorial Boards
  - Talks Committee
  - Analysis Reviews

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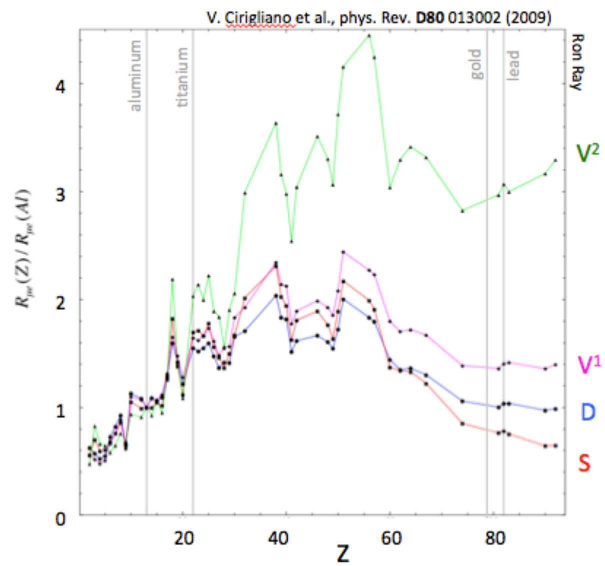
Project Status

- We have made excellent progress in the past 18 months
  - R&D for superconductor nearly complete – significant risk reduction that makes for simpler solenoids
    - Ready to purchase production conductor in early 2014
  - Reference designs completed for solenoids. Specification and Bid packages for design/build contracts ready to hit the street for Production and Detector Solenoids
    - Ready to obligate funds for final design in early 2014
  - 100% design from A&E in hand for detector hall. Bids on the street in early 2014.
    - Site prep begins in summer. Construction in the Fall
  - R&D on tracker, calorimeter, cosmic ray veto, DAQ all on track
- Obligated nearly $40M thus far (nearly 20% of total)
- We are maintaining a technically limited schedule.

Mu2e-II

- Mu2e uses 8 kW proton beam from Booster
- PIP II provides an upgrade path to x10 more beam power
  - Narrower proton pulses
  - No pbar background
  - Flexible beam structure
  - Run simultaneously with g-2
  - Requires some modest upgrades to Mu2e apparatus to handle higher beam power.
  - Important physics goals regardless of results from first phase of Mu2e.
    - More beam power for a more sensitive search
    - Flexible time structure of PIP II beam allows access to different stopping target nuclei where model dependent effects vary significantly.



(See arXiv:1311.5278 [hep-ex] for details)

Summary

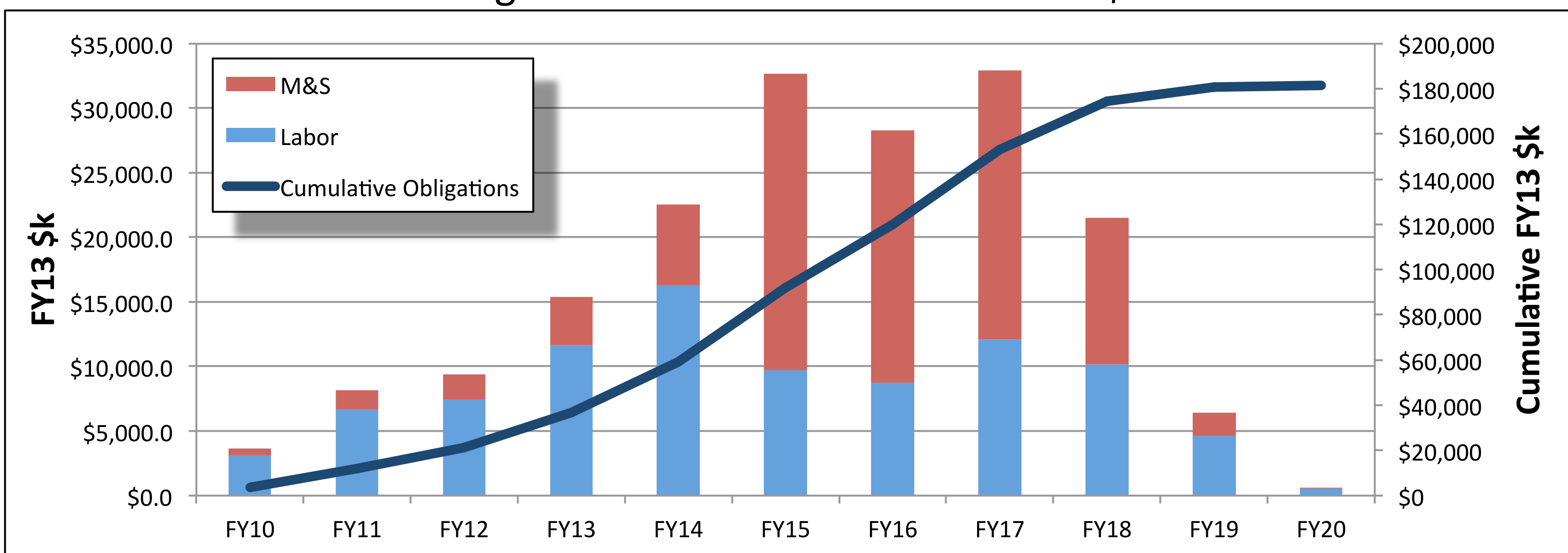
- Mu2e has discovery sensitivity over a wide array of physics models and probes the underlying physics in unique ways that connect strongly to the Energy Frontier and the rest of the Intensity Frontier program.
- PIP II provides an upgrade path to x10 more sensitivity and the ability to untangle physics models.
- DOE Facilities Panel concluded that Mu2e is ***absolutely central*** to the goals of particle physics in the US over the next decade.
- Since the previous P5 gave high priority to Mu2e, we have received CD-1 have spent significant project funds. We are on track to initiate construction in FY2014.

Backup Slides

Preliminary Cost Estimate in FY13 $

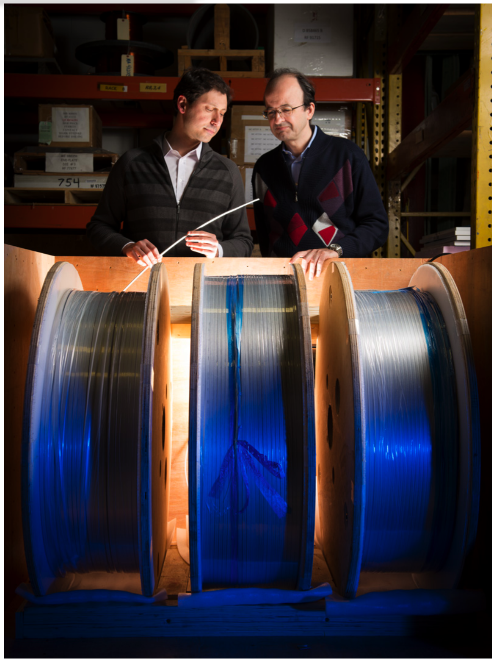
	Low	High
Actuals through FY13	$36,500	$36,500
Base Estimate to completion	$145,000	$153,000
Contingency on estimate to completion	$51,500	$54,000
Total	**$233,000**	**$243,500**

Obligation Profile – Base cost – FY13 $k



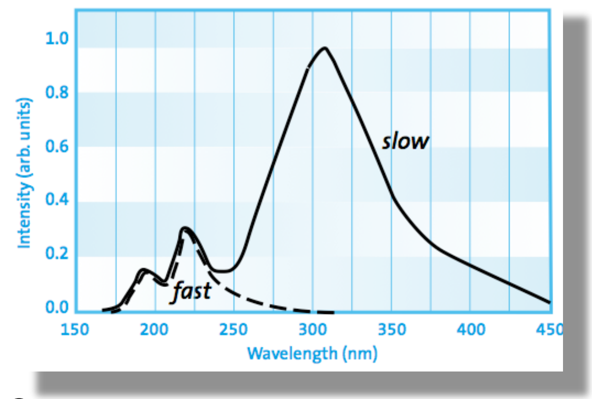
What R&D is still required?

- Solenoid conductor R&D is on the critical path and is nearly complete
  - CD-3a will authorize procurement of production conductor to keep the Project on schedule.
  - Successful conductor R&D validates decision to develop technically risky conductor in exchange for significantly simpler, cheaper, more robust solenoid designs.
- Production target studies at RAL
  - At 8 kW, target can be radiatively cooled
  - Measurements of tungsten emissivity, thermal fatigue
  - Evaluation of thin coatings to minimize oxidation in 10^{-4} – 10^{-5} Torr vacuum.



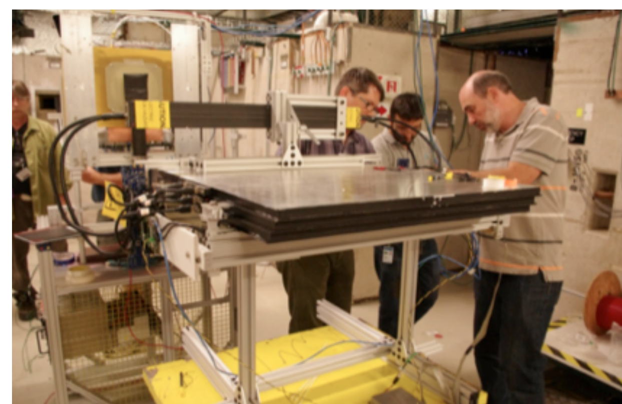
What R&D is still required?

- To offset dramatic price increase in LYSO crystals, we have switched to BaF2, saving > $6M.
  - BaF2 has a very fast component at about 220 nm and a slow component produced at longer wavelengths.
  - Requires UV extended photodetectors that can operate in a magnetic field.
  - Caltech is working with JPL and RMD to produce a UV extended device that is blind to longer wavelengths.
  - First wafers for UV extended response have been produced and are being tested. Blinding will be added in a subsequent round of wafers.



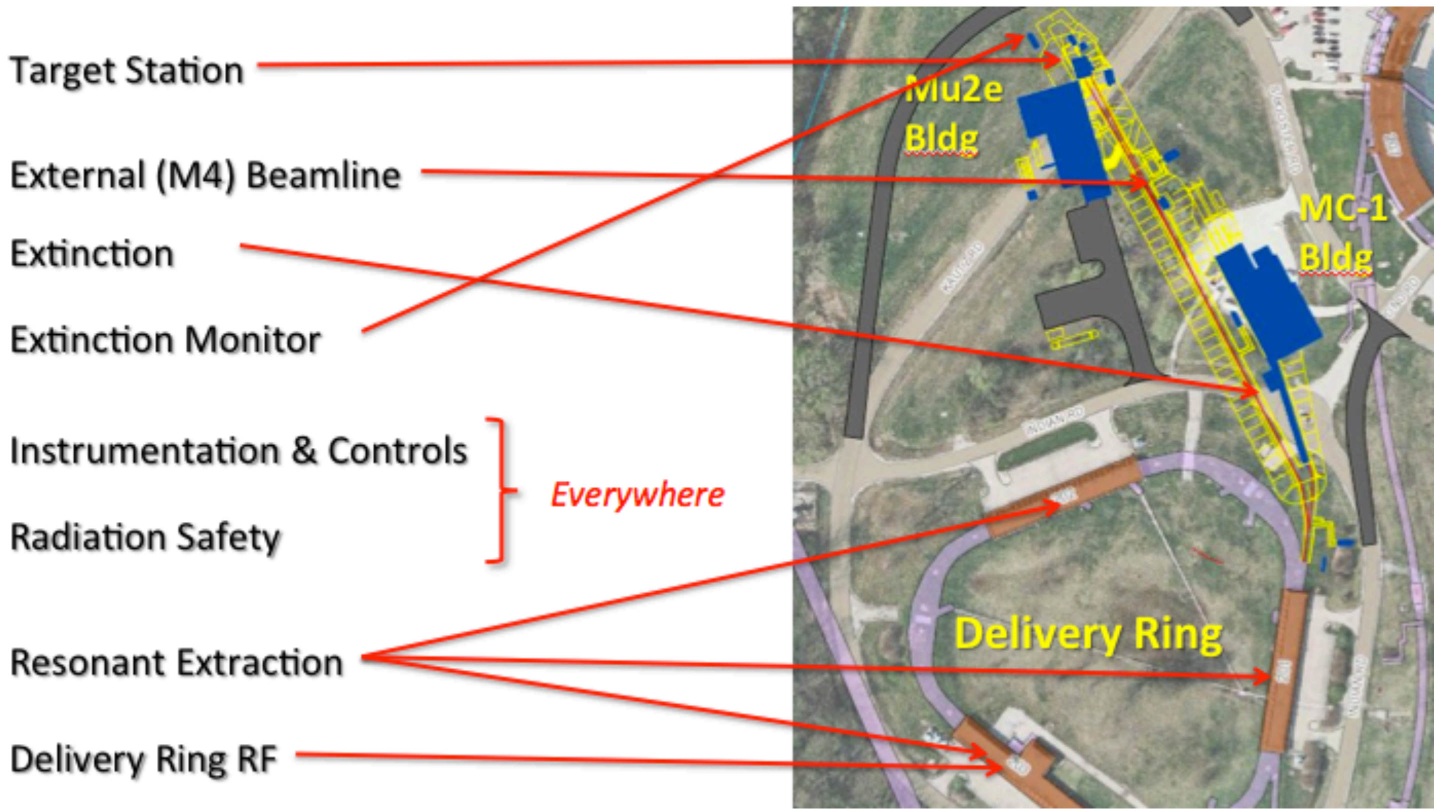
Other R&D

- Joint Mu2e/COMET beam test at PSI to measure byproducts from muon capture.
- Straw tube prototypes to operate in vacuum
- Beam tests to validate light output of Cosmic Ray Veto
- Beam test to evaluate concept for upstream Extinction Monitor
- Accelerator Beam Studies
- Radiation hardness studies
- Calorimeter beam tests
- Stopping target prototypes
- DAQ prototype
- Readout controller prototypes



Scope – Accelerator Upgrades

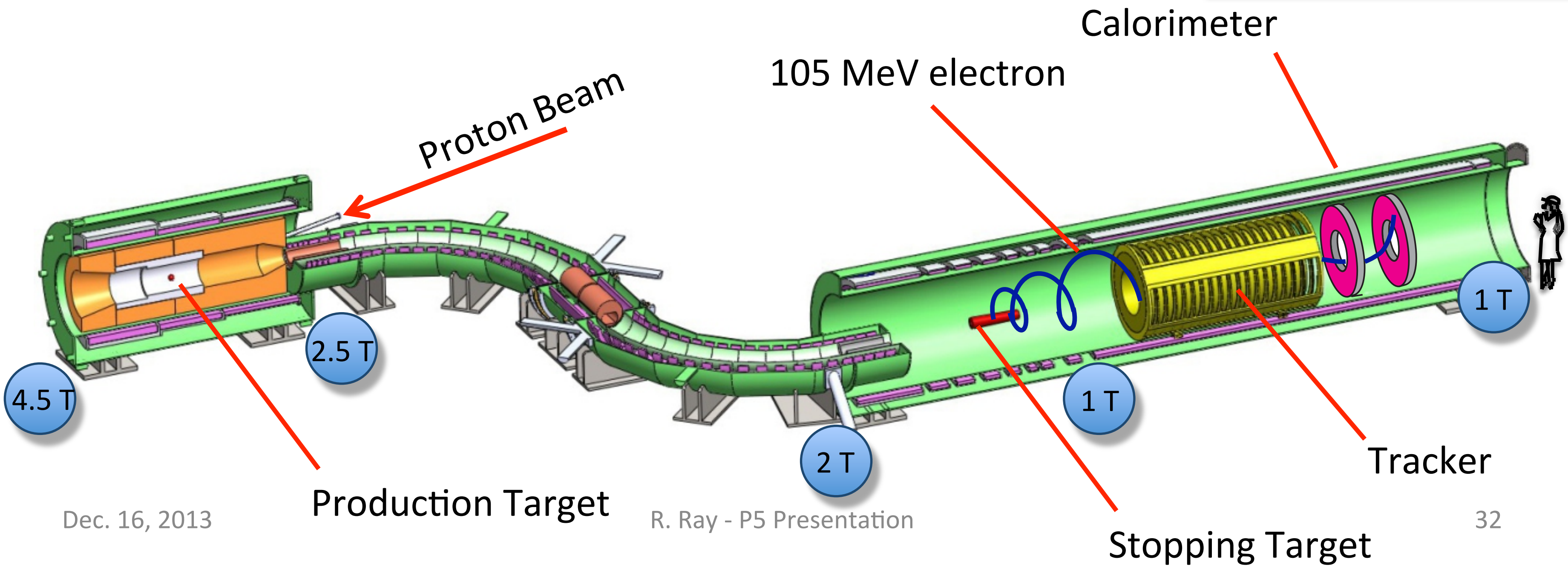
- Extract 8 kW of 8 GeV protons from Delivery ring to Mu2e with required pulse spacing and extinction between pulses.



Scope – Mu2e Apparatus

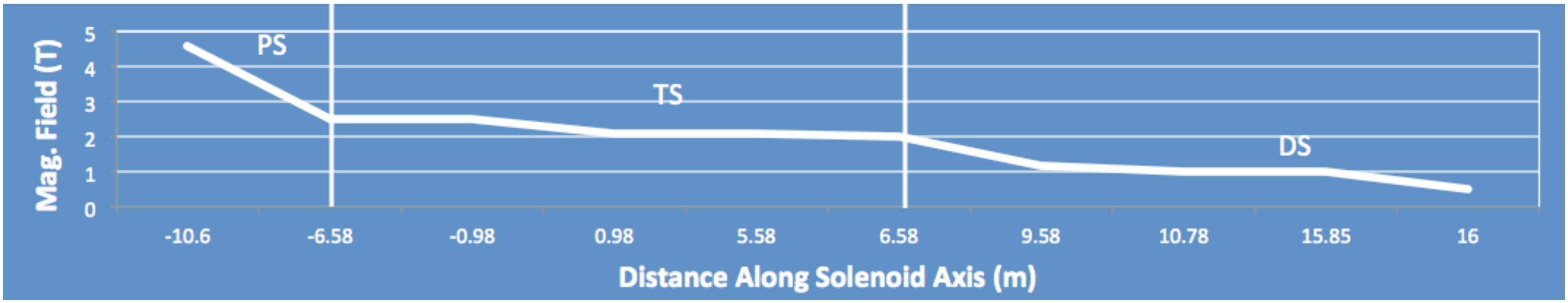
- Solenoids capture pions, form secondary muon beam, preserve timing structure, provide magnetic field for momentum analysis and help to reject backgrounds
  - Most efficient way of producing an intense, low energy muon beam
- 2 targets
- Tracker – Straw tubes
- Calorimeter – BaF2 crystals
- Cosmic Ray Veto – Scintillator, WLS fibers, SiPMs
- Stopping Target Monitor - Crystal

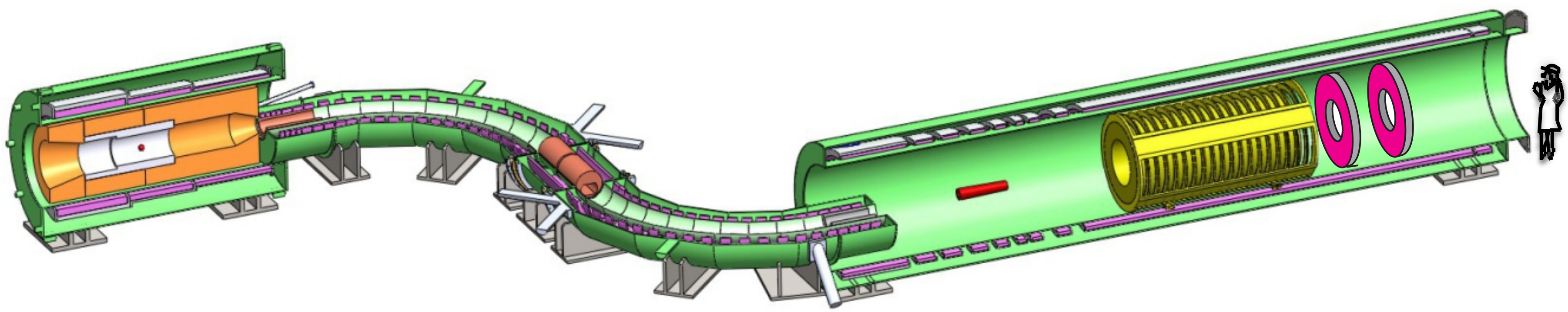
Cosmic Ray Veto and Stopping Target Monitor not shown



Scope - Mu2e Apparatus

Magnetic Field Profile – Driven by the science requirements



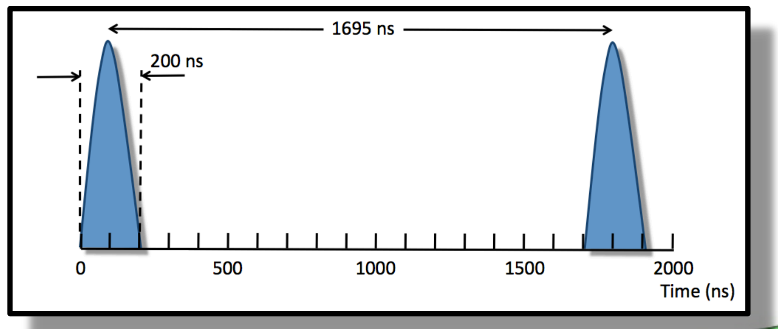


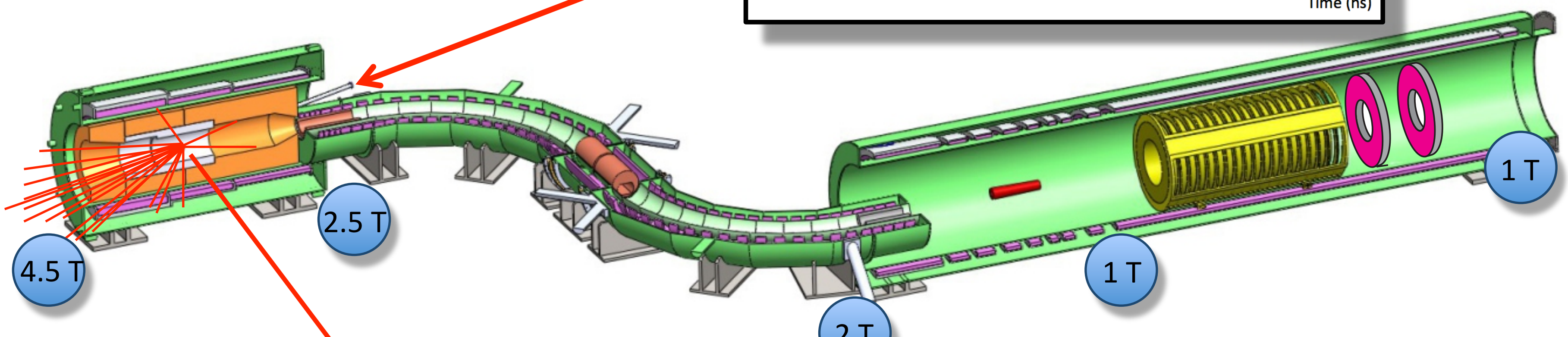
Scope – Mu2e Apparatus

Production Solenoid

- Production target
- Graded field
- Captures secondary pions

8 GeV protons



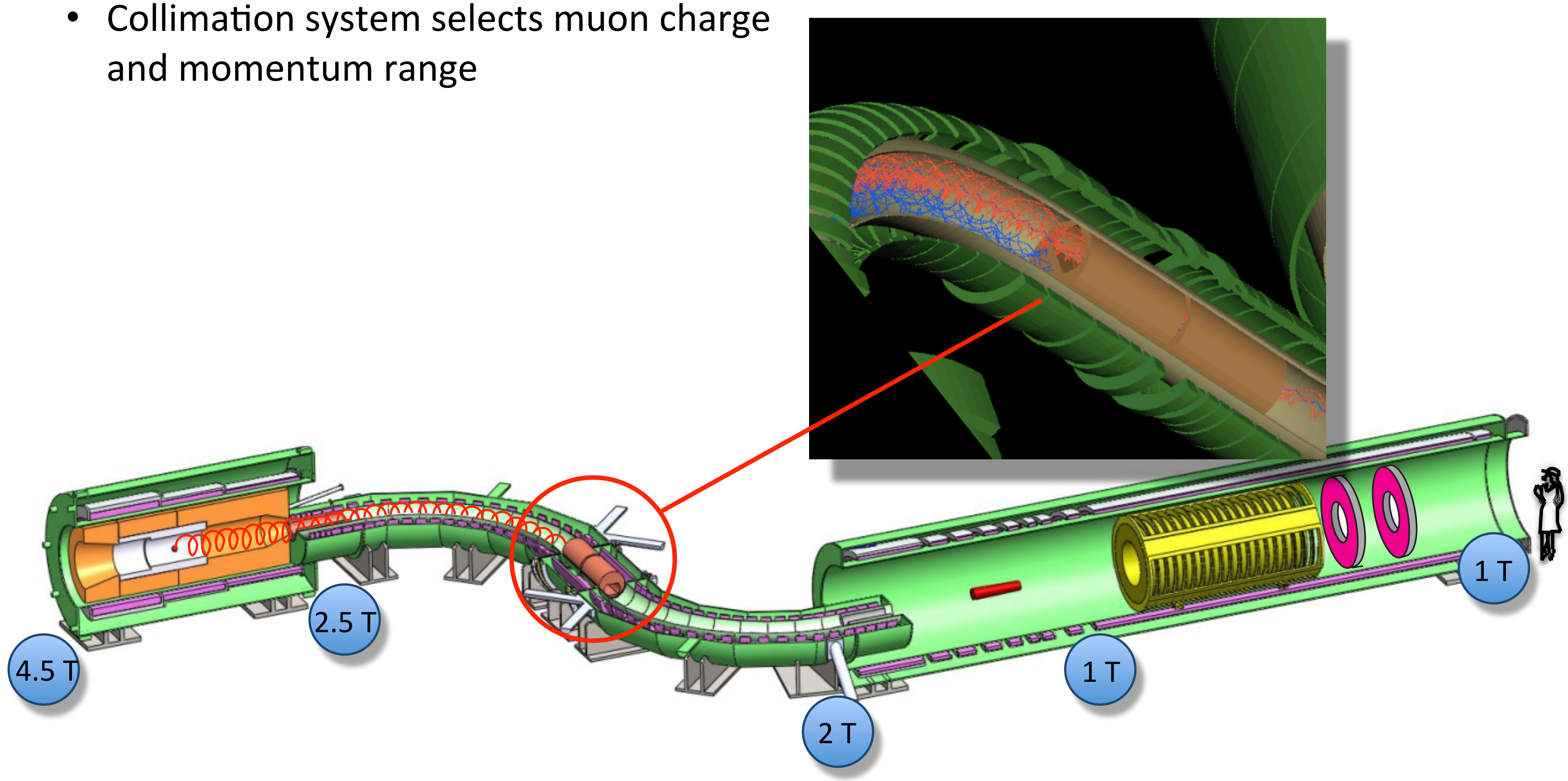


Production Target

Scope – Mu2e Apparatus

Transport Solenoid

- Collimation system selects muon charge and momentum range

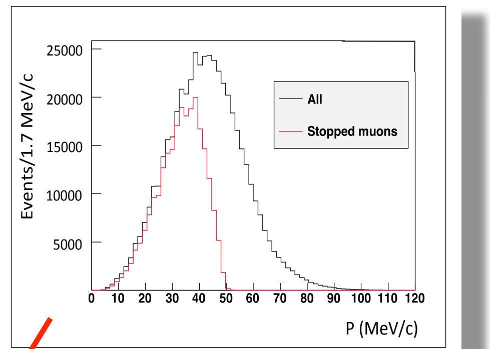


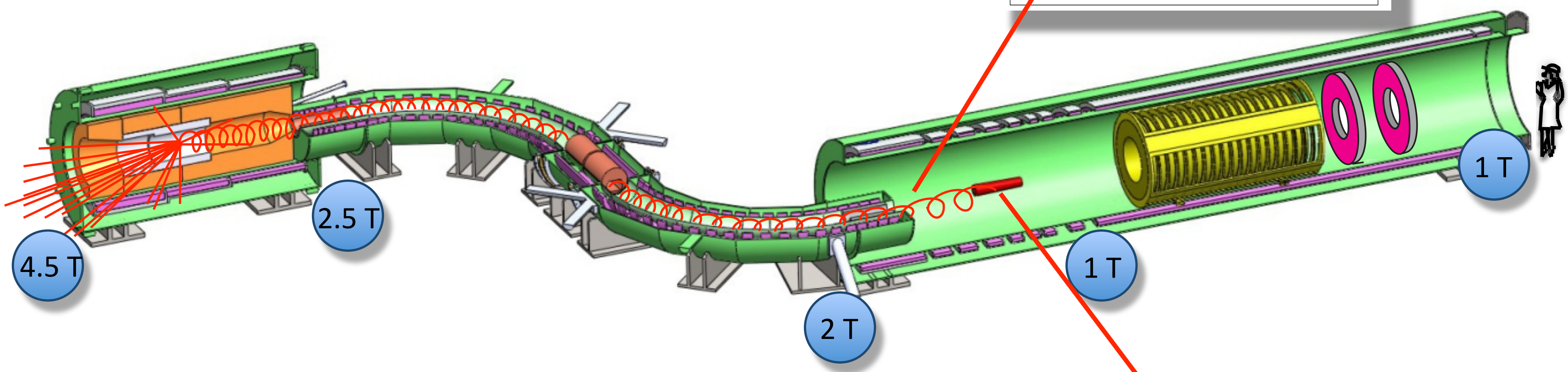
Scope – Mu2e Apparatus

Transport Solenoid

- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator
- Directs 10^{10} Hz of μ^- to stopping target

40 MeV/c μ^-



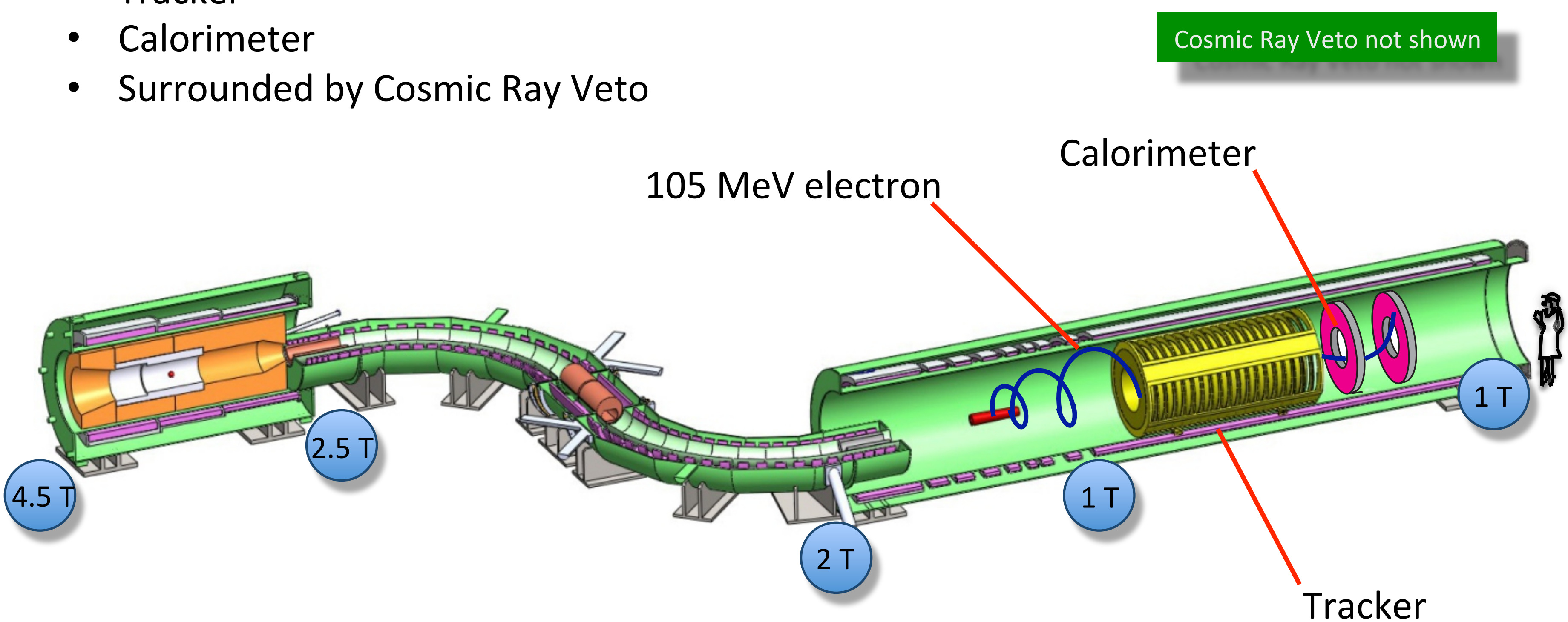


Stopping Target

Scope – Mu2e Apparatus

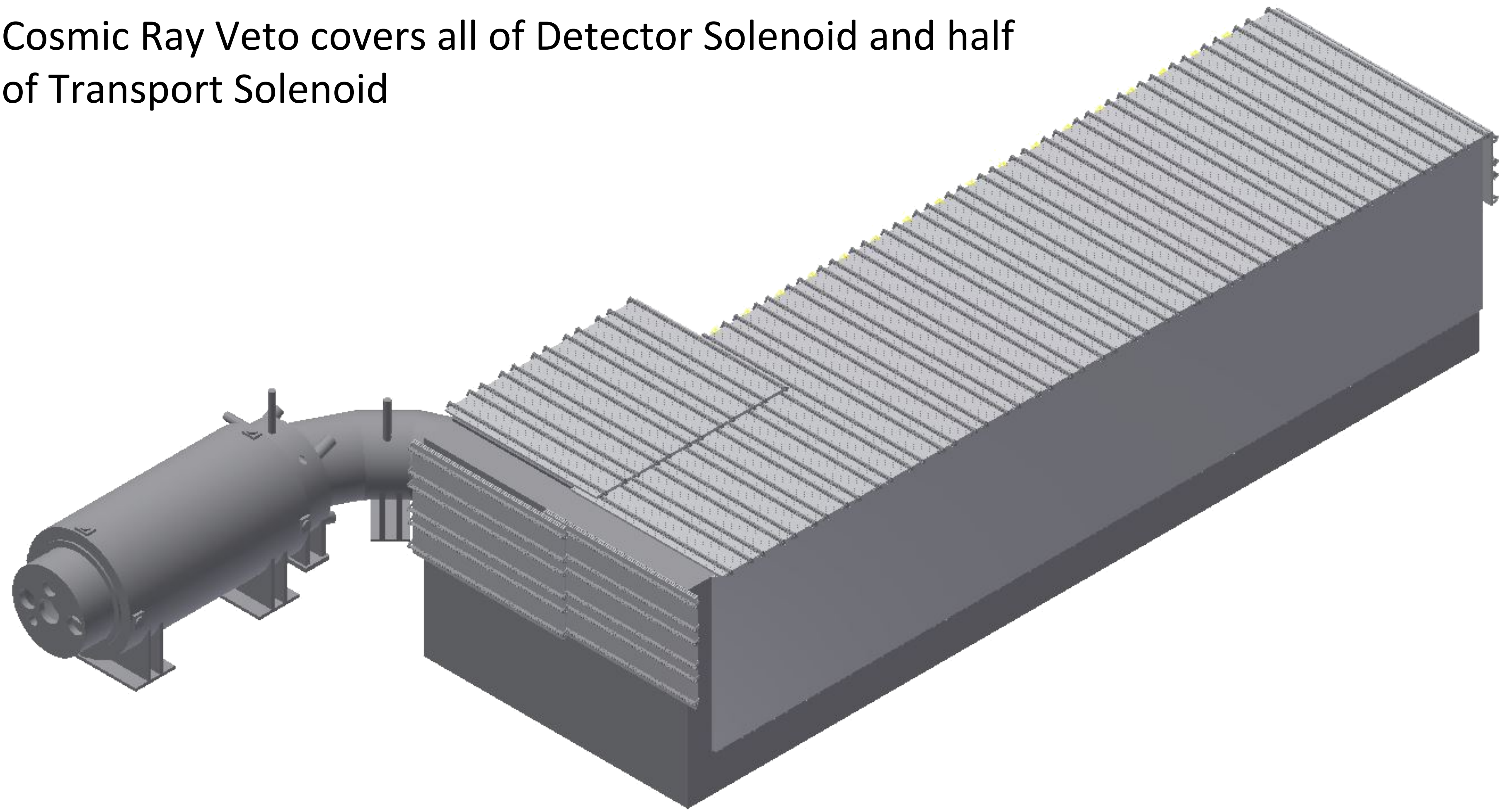
Detector Solenoid

- Graded field upstream for acceptance and background suppression
- Uniform field downstream for momentum analysis
- Muon stopping target
- Tracker
- Calorimeter
- Surrounded by Cosmic Ray Veto

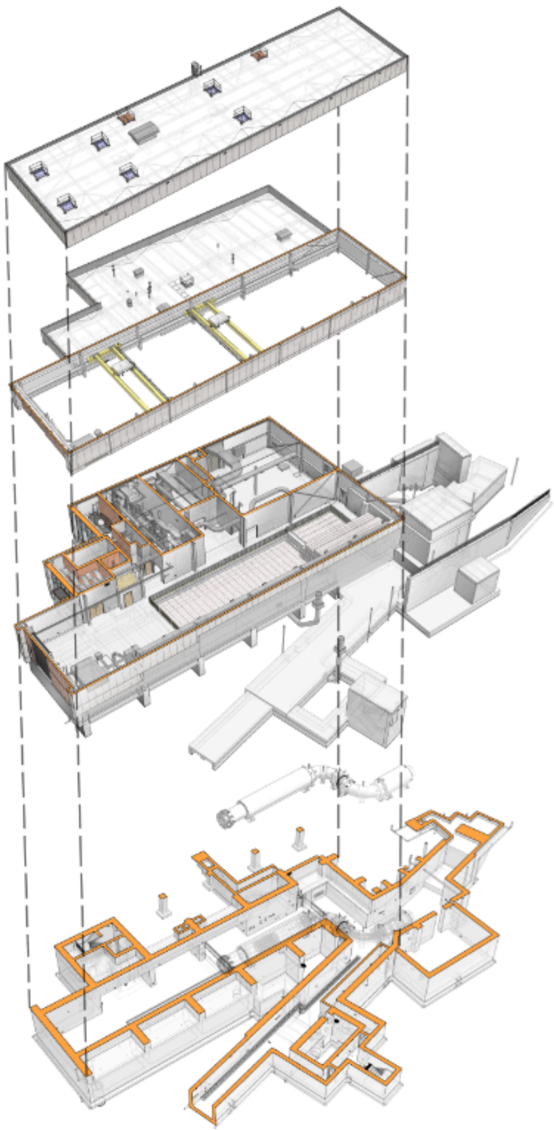


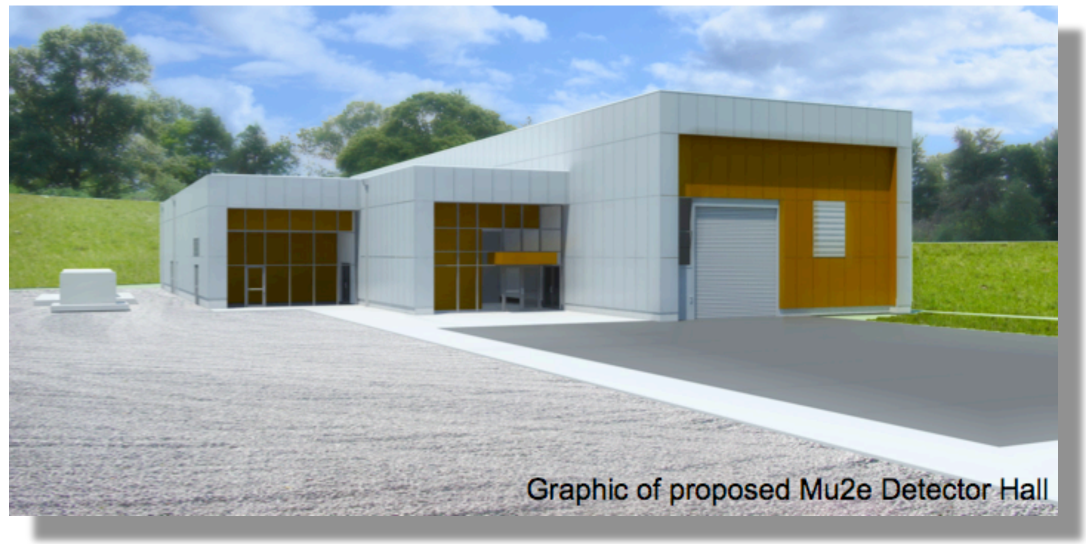
Scope – Mu2e Apparatus

Cosmic Ray Veto covers all of Detector Solenoid and half of Transport Solenoid



Scope – Experimental Hall





- 100% design from A&E in hand
- Solicit bids in early 2014.
- Bids in hand for CD-2
- Begin site prep work this summer
- Begin building construction on October 1 using FY14 construction funds.

The Last P5 – Apples to Apples

From Spreadsheet sent to Charlie Baltay ($M)

	FY11	FY12	FY13	FY14	FY15	FY16	Total
Accelerator, RF, etc,		3	3				6
Proton Beamline & Hall	5	9	9	5			28
Solenoids and Detector		16	33	32	11	2	94
Total	5	28	45	37	11	2	128

- Costs in FY08$
- No Project Management costs ~$18M
- No costed scientists
- Only G&A included in overhead (just one of several overhead multipliers)
  - G&A 10% in FY08
  - Full Fermilab overheads range from 70-97% in FY2014
- Proper application of all factors brings the 2008 P5 cost to over $200M

Thesis Topics

- In Conventional HEP/Nuclear Physics:
  - Mu2e Conversion with different reconstruction techniques
  - $\mu^{-}N(A,Z) \rightarrow e^{+}N(A,Z\text{-}2)$ (ΔL=2 process)
  - Precision measurement of muon Decay in Orbit spectrum
  - Mu2e Normalization mode (nuclear capture)
  - Radiative pion capture spectrum
  - Radiative muon capture spectrum
  - Beam related backgrounds
    - Electrons
    - Antiprotons
  - Calibration Measurements
    - $\pi^{+} \rightarrow e^{+}\nu$ (monoenergetic line)
    - Spallation muons
    - Michel edge

Thesis Topics

- Detector Development
  - Good at some foreign institutions
- In Accelerator PhD Program:
  - Extinction Method
  - Extinction Measurement
  - Slow Extraction
- Mu2e @ PIP II
  - All measurements with higher sensitivity and different target nuclei
    - Flexible time structure of PIP II beam allows access to different stopping target nuclei where model dependent effects vary significantly.

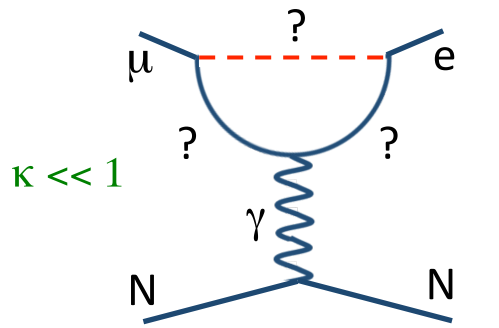
Model Independent Evaluation

A. de Gouvêa, P. Vogel
arXiv:1303.4097 [hep-ph]

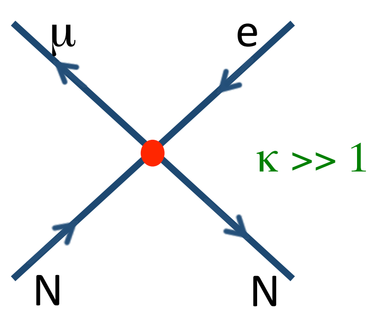
Add CLFV operators to SM Lagrangian.

$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\,\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\,\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L\right)$$

Λ is mass scale of new physics.
κ controls relative contribution of two classes of operators:



Loops



Contact Terms

Loops with photons contribute to $\mu \rightarrow e\gamma$

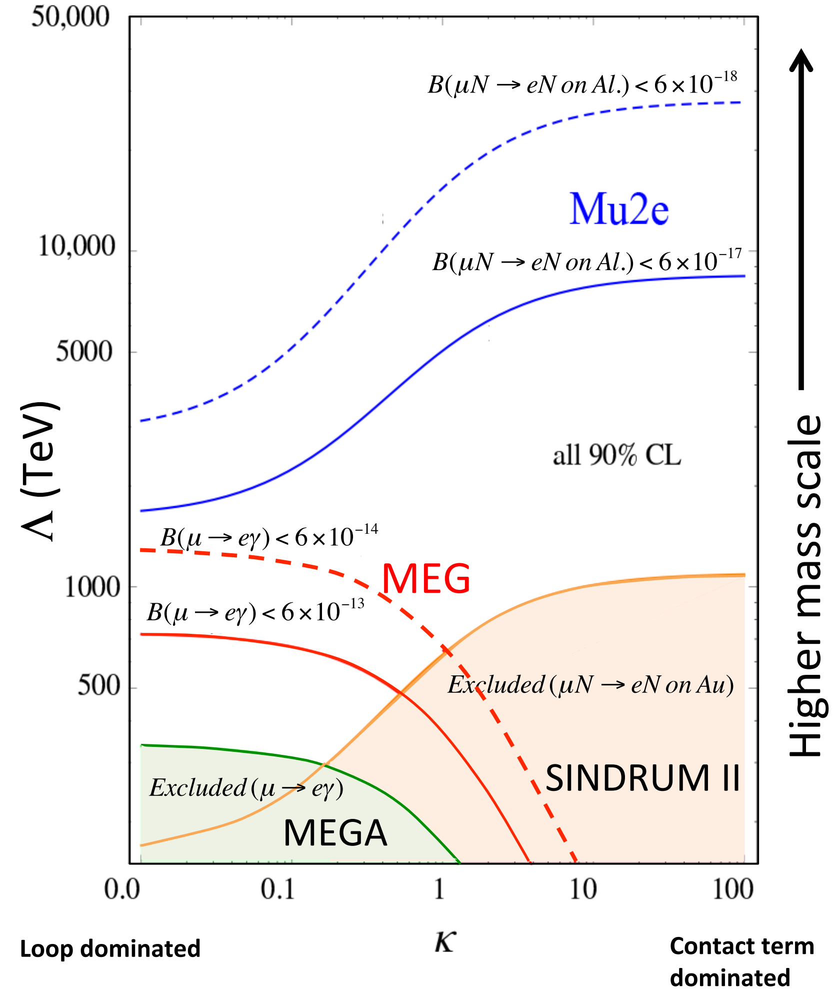
Does not contribute to $\mu \rightarrow e\gamma$

Both types of operators contribute to muon-to-electron conversion

Model Independent Evaluation

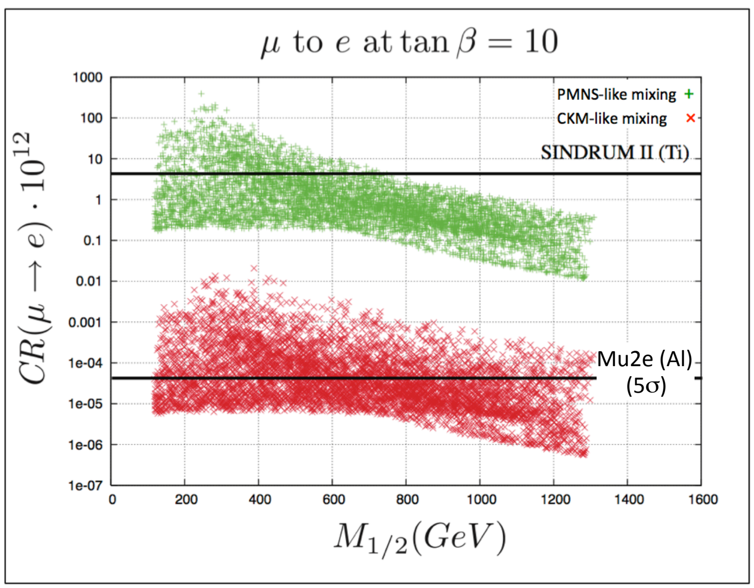
Mu2e offers world-class sensitivity across a broad array of New Physics models.

A. de Gouvêa, P. Vogel
arXiv:1303.4097 [hep-ph]

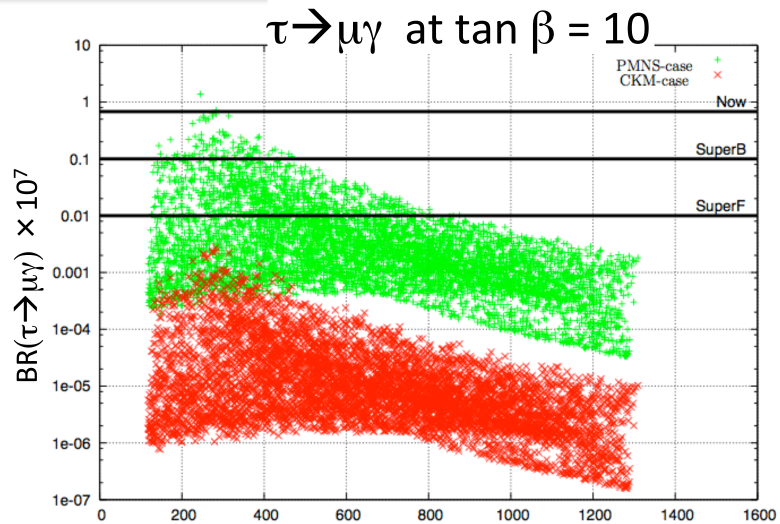


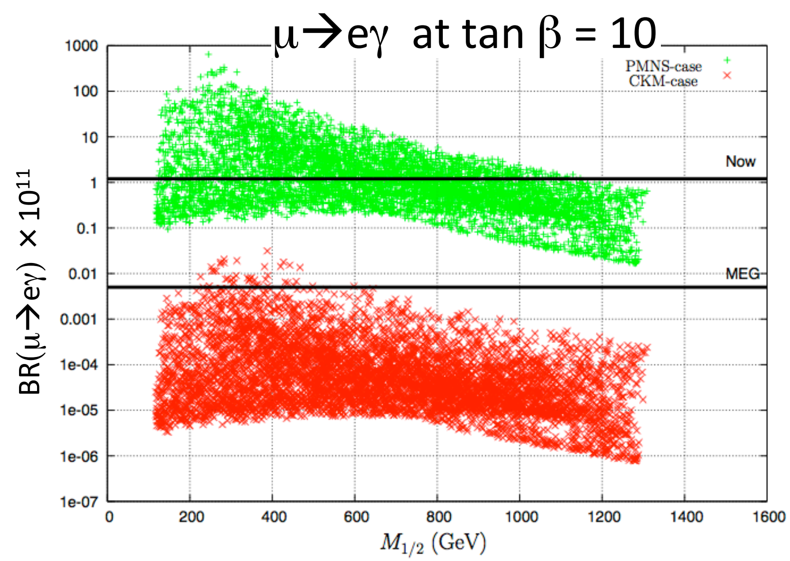
A Specific Model

- CLFV rates as a function of gaugino mass at the GUT scale for an SO(10) SUSY GUT model.
- Colors indicate different assumptions about neutrino Yukawa couplings.
- Muon-to-electron conversion has the greatest sensitivity.



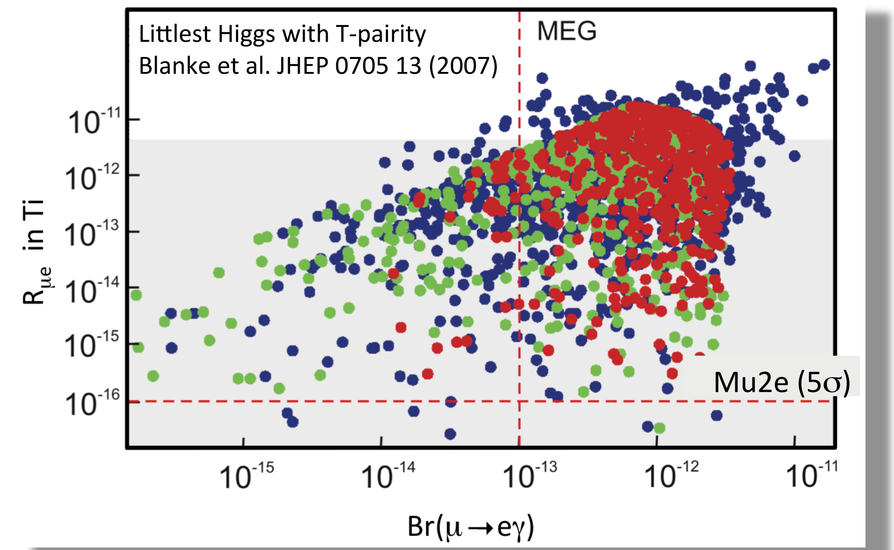
L. Calibbi et al. PRD **74** (2006) 116002



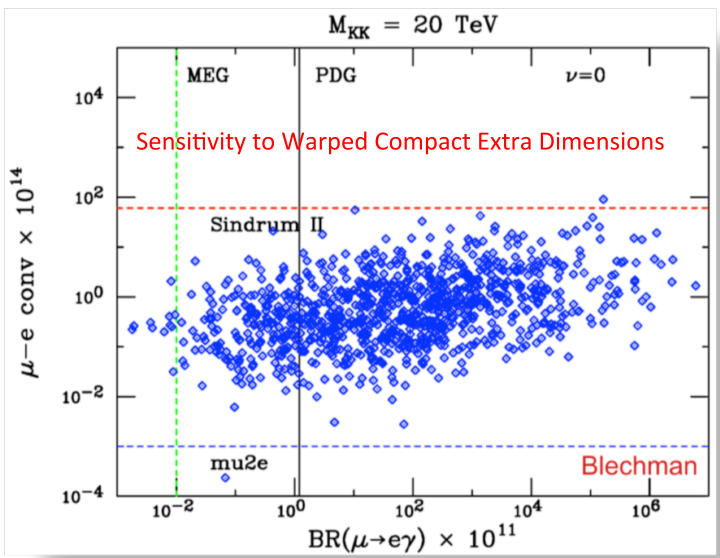


More Models

- Mu2e has sensitivity over this entire parameter space.
- Many examples illustrate the power of combined results.
- Rates and correlations of CLFV processes vary widely for different models.
- More measurements lead to greater discrimination power.



Littlest Higgs Model. The different colored points refer to different choices for the structure of the mirror-lepton mixing matrix that gives rise to the CLFV effects.



Scan of Randall-Sundrum Parameter space

World Competition

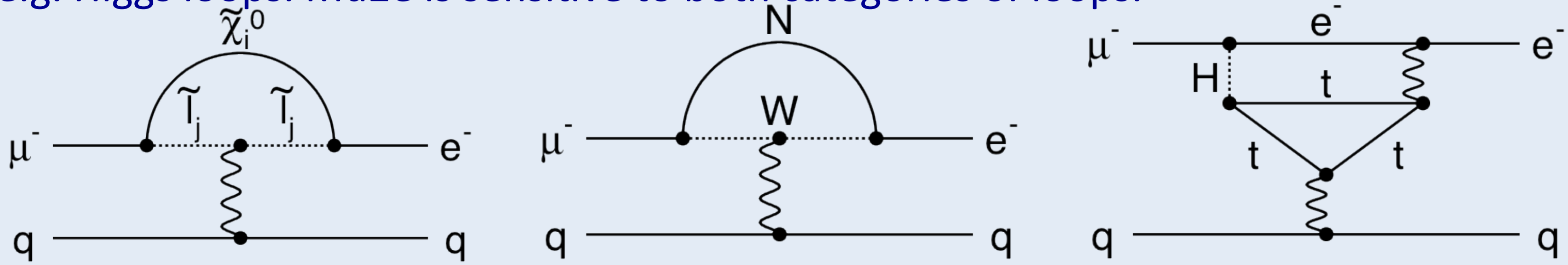
Significant interest in this physics on 3 continents

- PSI
  - MEG upgrade recently approved.
    - Resume data taking in 2016.
    - Estimated Sensitivity of 6×10^{-14} (90% C.L.)
    - Mu2e and MEG are both sensitive to new physics in loops
      - Mu2e has 2 times the physics reach for this physics compared to MEG
    - Mu2e is sensitive to new physics resulting from contact terms, MEG has no sensitivity to this physics.
      - Includes heavy neutrinos, additional Higgs doublets, heavy Z', anomalous Z couplings, etc.
  - $\mu^+ \to e^+ e^+ e^-$
    - Proposal recently approved.
    - Broader reach than $\mu \to e\gamma$, not as broad as Mu2e and does not access the mass scales available to Mu2e.
    - Data possibly available by the end of the decade. Competes with MEG for beam time.
  - PSI program and Mu2e are complementary. Combination with Mu2e is a powerful discriminator.

Mu2e and MEG

MEG is sensitive to loops with photon propagators. MEG is not sensitive to other types of loops e.g. Higgs loops. Mu2e is sensitive to both categories of loops.

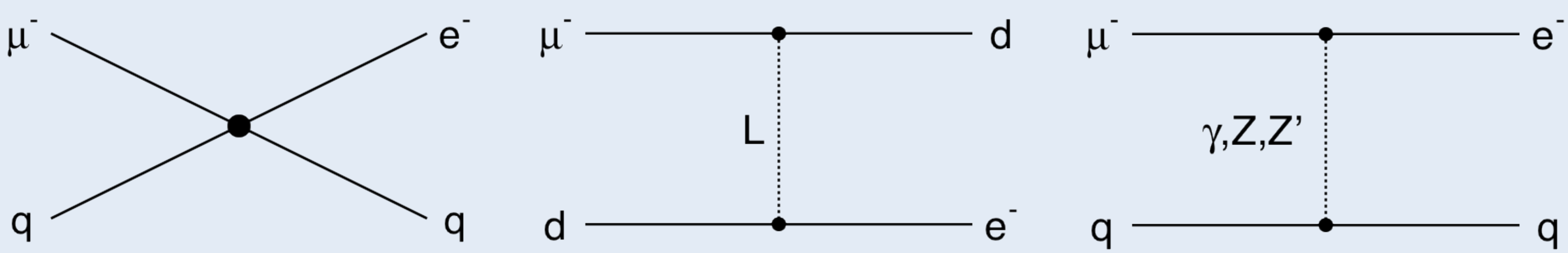
Loops



Supersymmetry Heavy Neutrinos Two Higgs Doublets

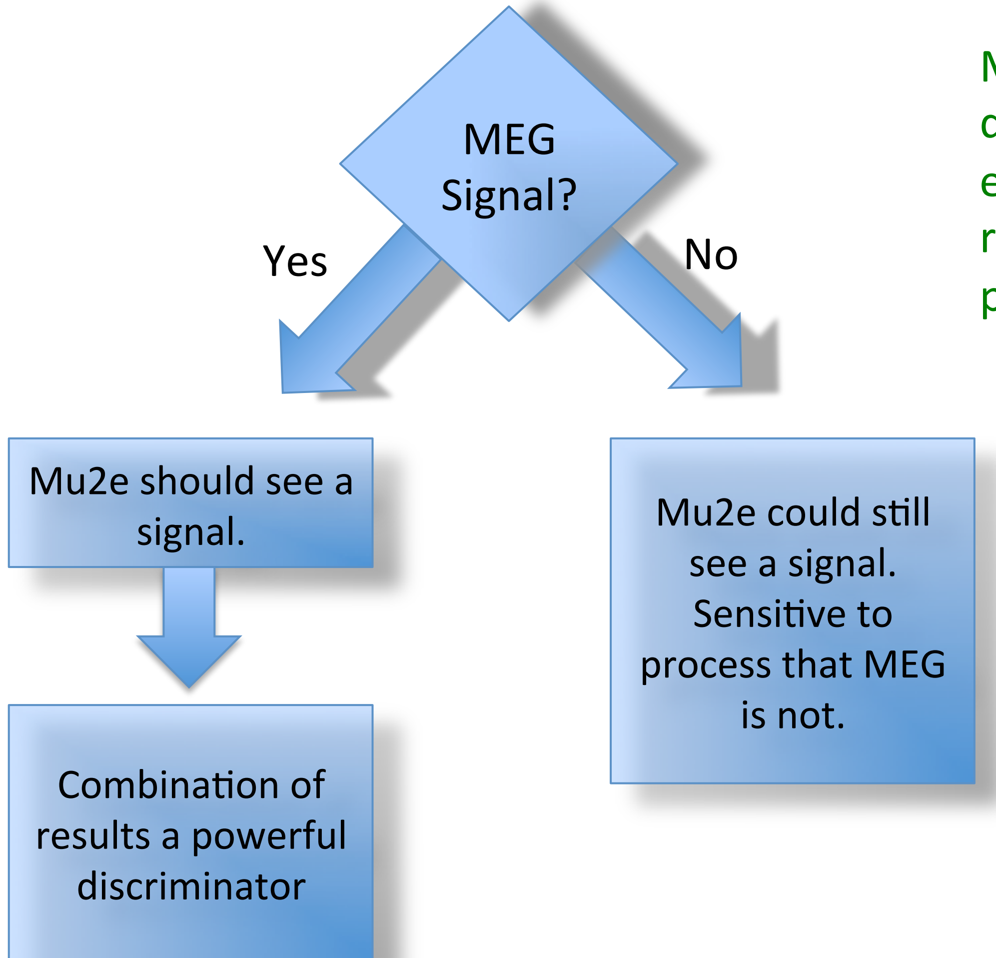
Contact Terms

Mu2e is sensitive to these. MEG is not.



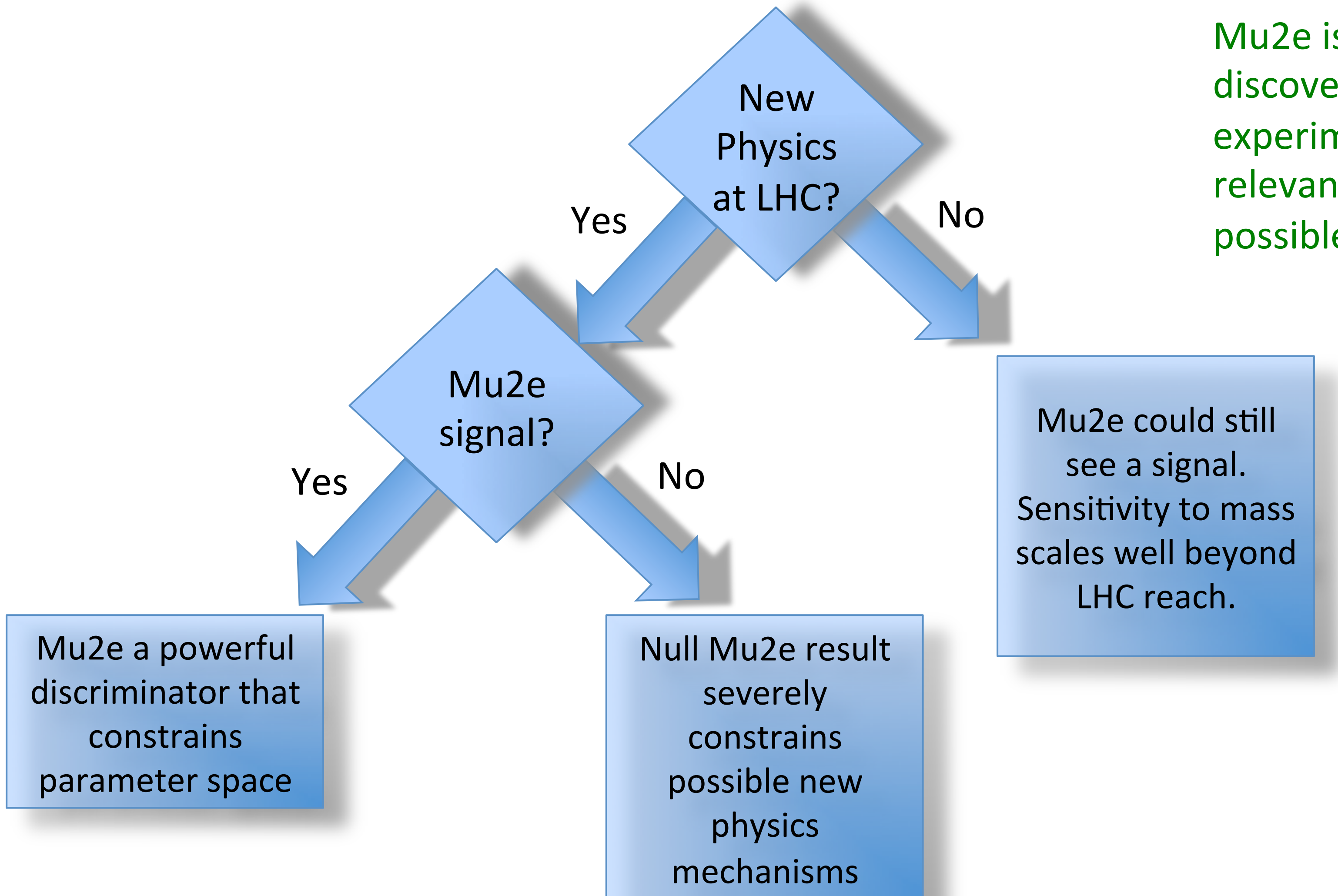
Compositeness Leptoquarks New Heavy Bosons / Anomalous Couplings

Mu2e and MEG



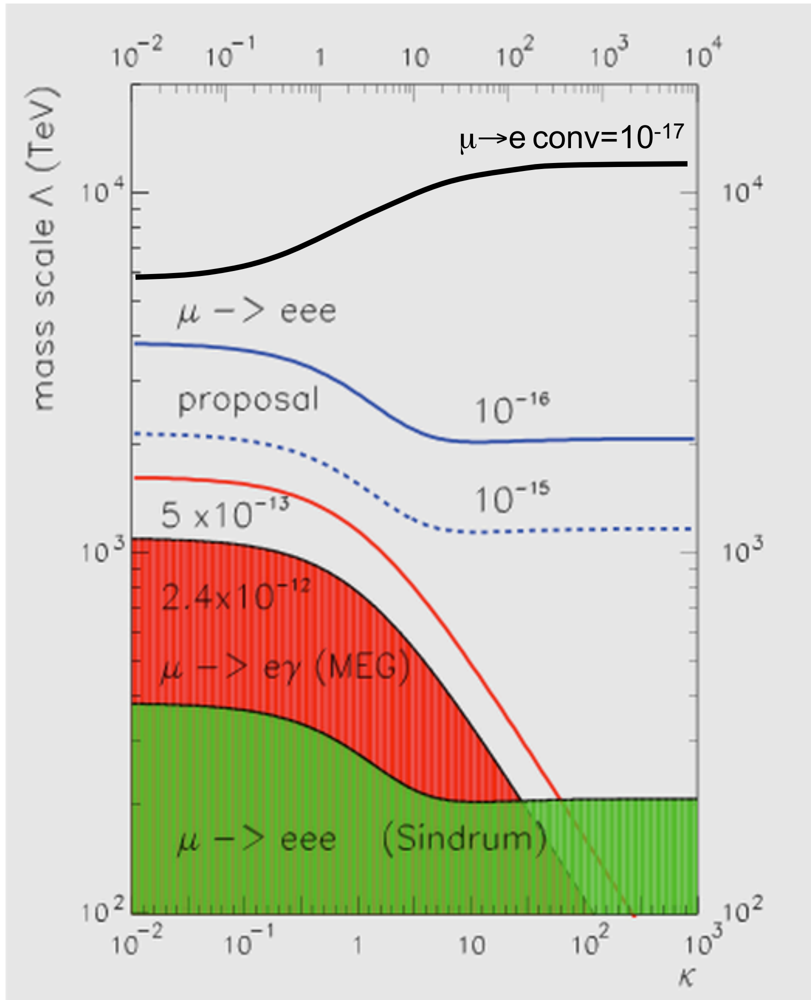
Mu2e is a potential discovery experiment that is relevant in all possible scenarios.

Mu2e and the LHC



Mu2e is a potential discovery experiment that is relevant in all possible scenarios.

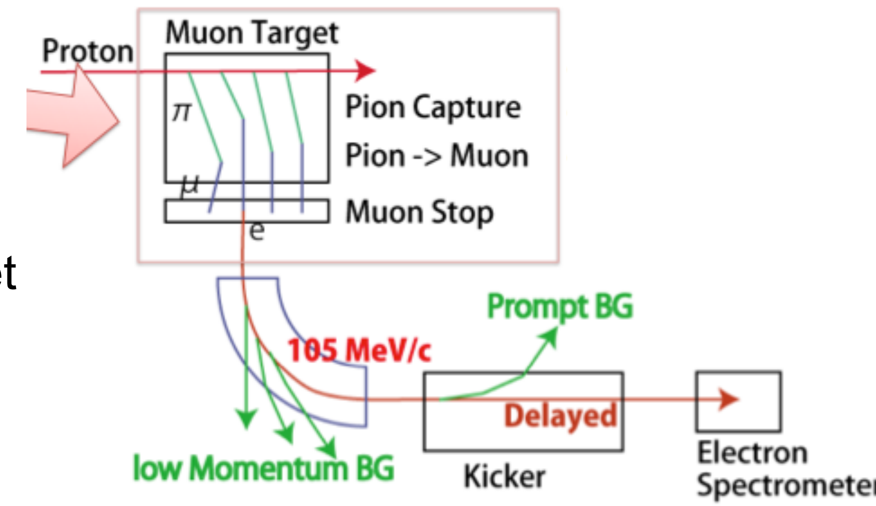
μ→eee



μ→e conv=10-17
μ -> eee
proposal
10-16
10-15
5 x10-13
2.4x10-12
μ -> eγ (MEG)
μ -> eee (Sindrum)
mass scale Λ (TeV)
κ
10-2
10-1
1
10
102
103
104

World Competition

- J-PARC
  - DeeMe – Muon Conversion
    - Look for muon conversion directly from production target
    - Aims for a sensitivity of 10^{-14}
    - Requires extraordinary extinction ~ 10^{-17}
    - Backgrounds still under study
    - Still in design phase.
    - Proposal suggests result in 5 years, before Mu2e or COMET.



World Competition

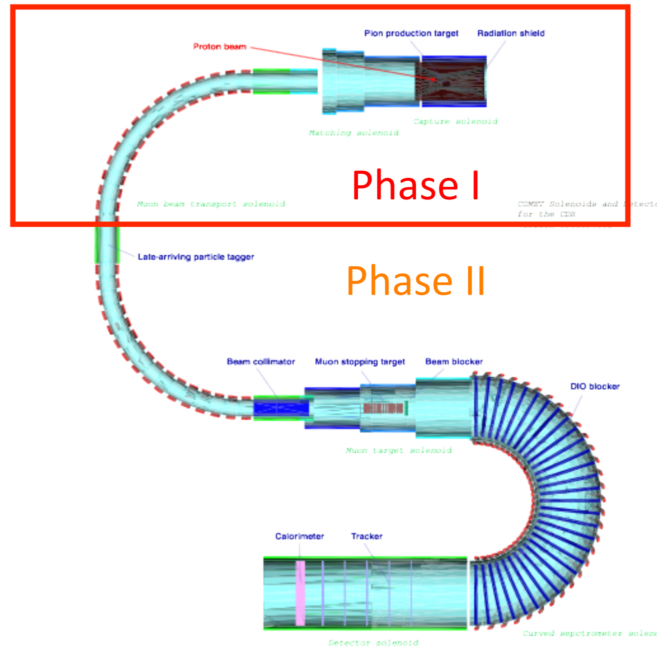
- COMET
  - Recently broken into 2 phases due to funding constraints.
  - Phase II reaches similar sensitivity to Mu2e
  - Proposed schedules similar.

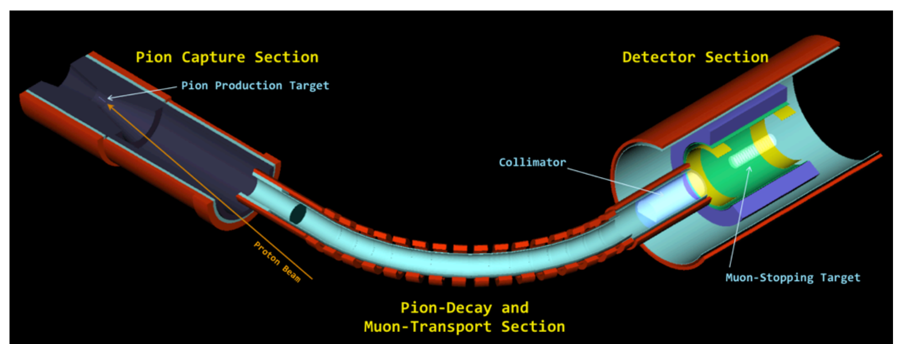
	SES	Background	Start Running
COMET Phase-I	3×10^{-15}	0.03	~2016
COMET PHASE-II	3×10^{-17}	0.4	~2020
Mu2e	2×10^{-17}	0.5	~2020

- Competition is indicative of compelling physics
- Confirmation of significant results by competing experiments could prove to be important.

Mu2e Phase I?

- COMET has established a first phase with a sensitivity of 10^{-15}
  - Very challenging measurement in the presence of high rate of neutrons and sea of low energy particles
- Would also measure backgrounds, particle rates out of first bend of their Transport Solenoid
  - Potentially very useful, though backgrounds in Phase II will be different than in Phase I.
- Should Mu2e consider a staging scenario?

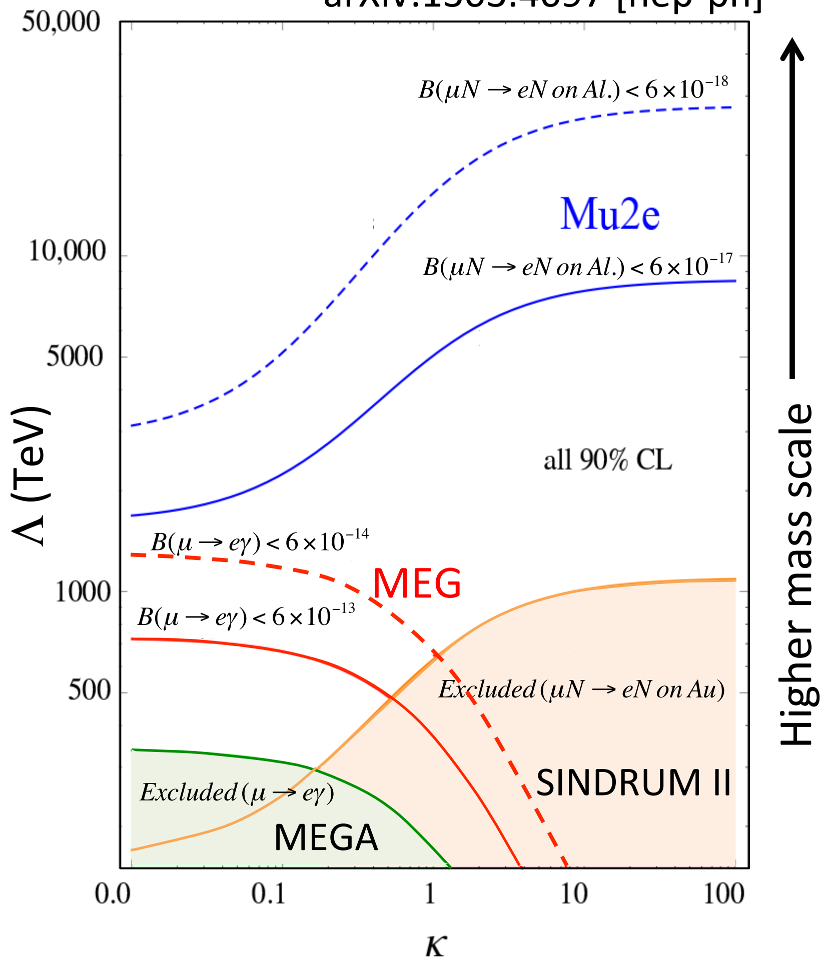




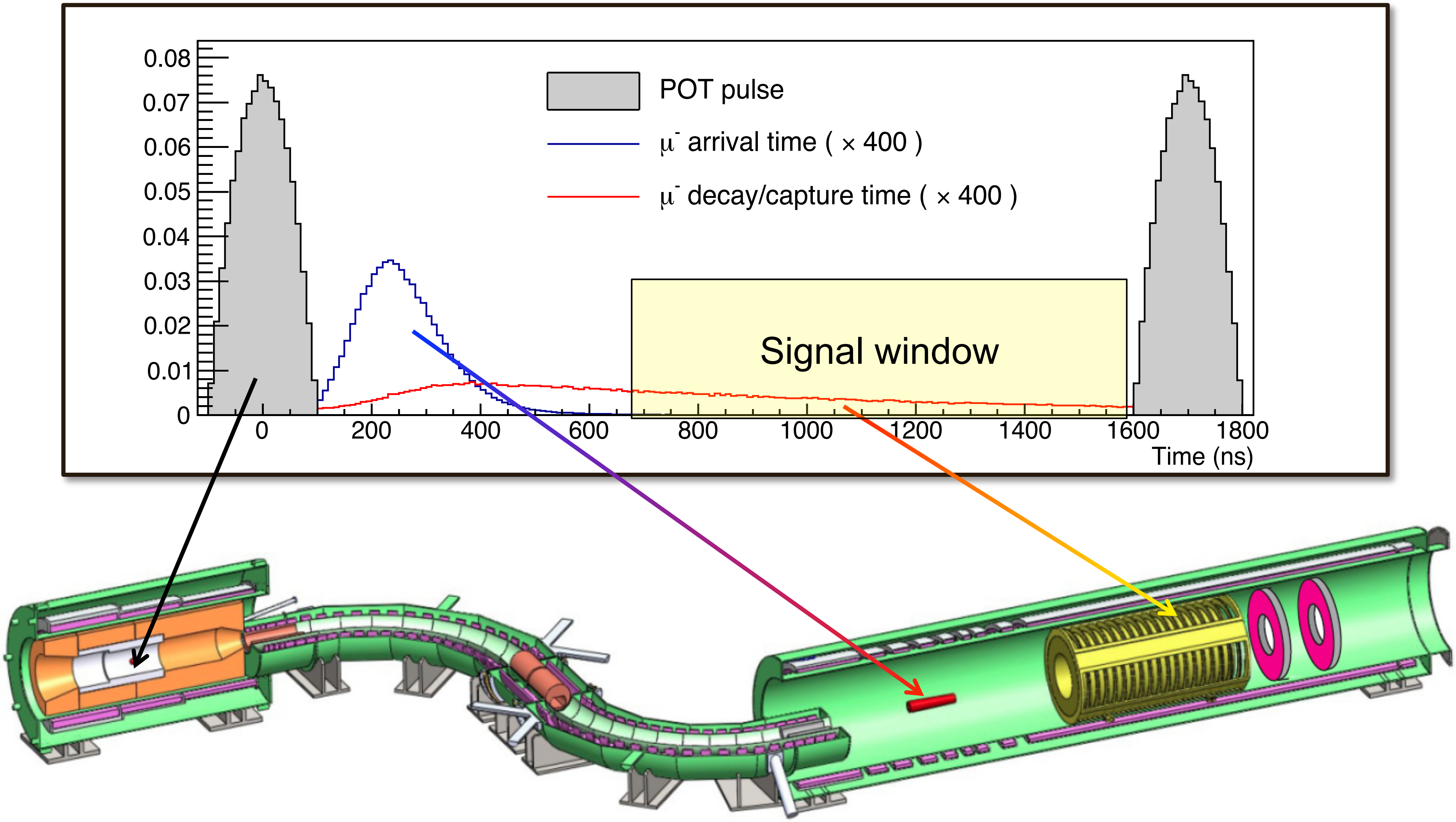
Mu2e Phase I?

- Staging delays the overall program and increases the cost of getting to 10^{-17} Sensitivity.
- Sensitivity of 10^{-15} from a Phase I experiment is 100x better than SINDRUM II for κ>>1 but is not competitive with MEG for κ<<1
- Staging requires a building, a beam, half of the solenoids, tracker, cosmic ray veto.
  - Significant fraction of the total cost.
- Full-scope Mu2e is the fastest, cheapest path to exploit full discovery potential.

A. de Gouvêa, P. Vogel
arXiv:1303.4097 [hep-ph]



A Muon Cycle



POT pulse
μ⁻ arrival time (× 400)
μ⁻ decay/capture time (× 400)
Signal window
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
200
400
600
800
1000
1200
1400
1600
1800
Time (ns)